NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3541

A METHOD FOR OBTAINING STATISTICAL DATA ON AIRPLANE VERTICAL VELOCITY AT GROUND CONTACT FROM MEASUREMENTS OF CENTER-OF-GRAVITY ACCELERATION

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SUMMARY

A method is presented whereby the contact vertical velocities of airplanes are obtained on a statistical basis from measurements of maximum incremental center-of-gravity acceleration. In order to evaluate this method, 268 landings with a small trainer airplane have been made. The vertical velocities obtained are compared with the actual vertical velocities obtained from a trailing-arm velocity indicator. The comparison is in the form of probability curves, and the difference in the two curves is less than 0.2 foot per second throughout the range of velocity covered in this investigation. This close agreement of the two sets of data indicates that a reliable probability curve for vertical velocity was obtained from the maximum incremental center-of-gravity accelerations. A limited amount of data for a medium bomber airplane is presented; these data indicate that the method is probably applicable to large airplanes.

INTRODUCTION

The vertical velocity of an airplane at contact is perhaps the basic factor in determining the landing-gear loads. There has been a continuing desire, therefore, to obtain more accurate information on this quantity in order to aid in the formulation of more rational landing-gear design criteria. Because the contact speed is influenced by many factors, it has been considered necessary to make use of a statistical approach wherein large quantities of measured vertical-velocity data are involved.

The various methods presently used to gather vertical-velocity data have provided useful information; however, each method requires a ground installation or a complex airplane installation. The data obtained with ground installations are descriptive only of landings occurring at certain preselected points and, as such, are not representative of the true flight history of an airplane.

The purpose of this paper is to evaluate a rather simple statistical method for obtaining cumulative probability curves of vertical velocity from measurements of the maximum center-of-gravity acceleration obtained through use of a single light accelerometer carried in the airplane. Since all landings are recorded, the possibility of bias arising from selective recording of the data is eliminated. This paper presents a description of the method together with an evaluation of results obtained from a flight program consisting of 268 landings made with a small trainer airplane. Also presented are results obtained with a similar trainer airplane as well as data for a medium bomber airplane.

BASIC CONCEPTS AND DESCRIPTION OF METHOD

This paper presents an experimental method for obtaining the cumulative probability distributions of vertical velocity of airplanes at ground contact. A basic concept of the method is that the maximum vertical incremental acceleration of the center of gravity (the total acceleration less the acceleration due to wing lift, assumed herein to be 1g) is primarily a function of the vertical velocity of the airplane at the instant of ground contact. The relationship between maximum incremental acceleration and vertical velocity during landing was derived in reference 1 wherein the acceleration was shown to depend on a number of other variables such as weight, tire deflection, and orifice area at maximum acceleration. In addition to the variables considered in reference 1, there are factors which have an effect on the acceleration during actual landings of aircraft such as unsymmetrical impact, angular motion, and so forth. However, examination of flight-test data gathered in the past has indicated that the vertical velocity and the maximum incremental center-of-gravity acceleration were closely interrelated. This interrelation seemed to indicate that the effects of the other variables were either small, self-canceling, or associated with vertical velocity. The implication of the foregoing discussion is that explicit consideration of all other variables might be avoided and that acceleration measurements alone might provide a basis for determining the vertical velocities at the instant of ground contact. Application of this concept must necessarily employ statistical methods.

The method evolved for application of the above principle consists in making a limited number of landings with a particular airplane during which the maximum vertical accelerations of the center of gravity and the ground-contact vertical velocities are measured. These landings should cover as large a portion as practicable of the design vertical-velocity range of the airplane. The values obtained for vertical velocity and maximum incremental acceleration are examined and a definite relationship between the two variables is noted (despite some scatter which is due to the influence of other variables, as discussed previously). However, if the scatter is relatively small (that is, if the correlation between vertical velocity and incremental acceleration is close), the average variation of maximum incremental acceleration with vertical velocity provides a useful means of determining the vertical velocity from measurements of acceleration increment. This average relationship can be considered to be an effective calibration curve for vertical velocity and may be determined by least-square techniques. Once this calibration curve has been established, subsequent vertical-velocity values are obtained by simply measuring the maximum vertical incremental acceleration of the center of gravity for each landing and referring this value to the calibration curve. It should be pointed out that the value obtained for each landing is not necessarily the actual value of vertical velocity for that particular landing; but, for a sufficient number of landings, values on the average should be accurate enough to allow the construction of a valid vertical-velocity probability curve for the particular airplane, which is the ultimate aim of the method.

EQUIPMENT AND INSTRUMENTATION

In order to test the foregoing concepts, experimental data were obtained during landing impacts of a two-place trainer airplane (fig. 1) having a gross weight of 5,200 pounds. The trailing-arm vertical-velocity indicator described in reference 2 was mounted on the left landing gear of the airplane and was used to measure the vertical velocity of the airplane at the instant of ground contact of the left main wheel.

A strain-gage accelerometer was mounted near the center of gravity in order to measure the center-of-gravity accelerations. The instant of contact of each of the main wheels was indicated by the output of strain-gage accelerometers mounted on the lower mass of each landing gear.

The output signals of the velocity indicator and instant-of-contact accelerometers were recorded with galvanometer elements having a flat-response range from 0 to 5 cycles per second. These low-frequency galvanometers were used in order to reduce the extraneous high-frequency vibration picked up by the trailing-arm velocity indicator. The output signal of the accelerometer near the center of gravity was recorded on a galvanometer element with a flat-response range from 0 to 100 cycles per second. All galvanometers were electromagnetically damped at approximately 65 percent of the critical damping.

SOURCE OF DATA

Seventy-eight landings were made to determine the vertical-velocity calibration of the airplane in terms of the maximum vertical acceleration increment of the center of gravity. The vertical velocities are those recorded at the left landing gear since the trailing-arm velocity indicator was installed only on the left gear. However, in 80 percent of the landings, initial contact occurred on either the left wheel or on both wheels at the same time. The maximum incremental center-of-gravity acceleration ranged from 0.20g to 2.64g, and the vertical velocity at the time of contact of the left main wheel ranged from 1.0 to 9.1 feet per second. An effort was made to get very low and very high vertical velocities in order to obtain a reliable relationship between the incremental center-of-gravity accelerations and vertical velocity over the full range of vertical velocity. The airplane attitude at the time of ground contact ranged from the level to the three-point attitude.

In order to test the method, 190 routine landings were then made. The pilot was requested to make routine landings in order to obtain a sample indicative of normal operations. The maximum incremental center-of-gravity acceleration ranged from 0.07g to 1.36g, and the vertical velocity at the time of left-wheel contact ranged from 0.3 to 5.2 feet per second. All landings were made in the daytime on dry concrete runways at two airports during the months of October through February. The temperature ranged from 28° to 72° F at the time the landings were made. Cross winds up to 25 miles per hour were encountered in some of the landings. Each of four pilots flew the airplane in order to minimize the effects of individual piloting techniques.

EVALUATION OF METHOD

In order to evaluate the method, the 78 landings were used to establish a calibration curve of the airplane. The acceleration measurements obtained in the 190 routine landings are referred to this calibration curve in order to obtain an estimated probability or frequency-distribution curve for these landings. These estimated frequency distributions are then compared with the actual frequencies as obtained from the trailing-arm measurements from these 190 landings. Table I presents the experimental data obtained during the 78 calibration landings and the 190 routine landings. Included in the tabulation are the maximum incremental center-of-gravity accelerations, which are defined as the maximum accelerations at the center of gravity less the assumed value of 1g due to wing lift. The tabulated vertical velocities are the values obtained from the trailing-arm velocity indicator at the time of contact of the left main wheel.

The data from the 78 landings together with the calibration curves are plotted in figure 2. The calibration curve represented by the solid line was determined by assuming a linear relationship between the vertical velocity and maximum acceleration and fitting a straight line to the experimental data by the method of least squares. Although the true curve is not expected to be linear, a straight line yielded as good a representation of the data for the range covered as any of several curves which were tried. It is possible, however, that nonlinear calibration curves might prove more suitable for some other types of airplanes. The dashed curve in figure 2 is the calibration curve for another airplane of the same type and will be discussed subsequently herein. The values of maximum incremental center-of-gravity acceleration obtained during the routine landings (79 to 268 in table I) were used to determine vertical velocities by referring them to the calibration curve. A comparison of these velocities with those obtained from the trailing-arm velocity indicator is shown in figure 3.

Comparison With Trailing-Arm Velocity Data

In order to test the reliability of the method, a statistical comparison was made between the vertical velocities obtained from the accelerations and those obtained from the trailing-arm velocity indicator. Pearson's Type III frequency curves (ref. 3) were fitted to the distributions for the trailing-arm data and the acceleration data. (See fig. 4.) The dashed line represents the velocities obtained from the acceleration data whereas the solid line represents the velocities obtained from the trailing arm. The shapes of the two distributions are very similar and each set of data has the same value of standard deviation, namely, 0.94 foot per second. The apparent displacement of the distributions relative to each other, however, is reflected in the means, the modes, and the coefficients of skewness. For the trailing-arm data, the mean is 1.79 feet per second, the mode is 1.40 feet per second, and the coefficient of skewness is 0.83; for the acceleration data, these values are 1.95 feet per second, 1.52 feet per second, and 0.91, respectively. These differences are due chiefly to the data lying in the velocity range below 1.5 feet per second. This fact is illustrated in figure 5, where the ratio of the velocity obtained from the acceleration data to the velocity obtained from the trailing arm is plotted against the trailing-arm velocity. Most of the data below 1.5 feet per second on the abscissa tend to lie above the line of agreement. Calculations for both sets of data at velocities greater than a trailing-arm velocity of 1.5 feet per second gave a mean value of 2.44 feet per second for the trailing-arm data and 2.48 feet per second for the acceleration data.

The quantitative effect of the differences in the frequency distributions appearing in figure 4, which consists of the 190 routine landings, is illustrated by the cumulative vertical-velocity probability curves derived from each set of velocities. (See fig. 6.) Pearson's Type III curves (ref. 3) were used to provide a systematic method of fairing. In figure 6 it can be seen that the differences in the two sets of data result in probability curves which differ by less than 0.2 foot per second throughout the range of vertical velocity (0 to 5.2 feet per second) covered in this investigation. It is believed that this small discrepancy would prove to be relatively unimportant for landing-gear design purposes. The close agreement of the two sets of data indicates that, for the 190 landings used in this investigation, a reliable cumulative probability curve for vertical velocity was obtained for this airplane from the maximum incremental center-of-gravity accelerations. The points on the curves are the cumulative frequencies. Not too much significance should be attached to the points at the higher velocities since they are based on just one or two landings. In order to obtain a more extensive confirmation of the method for this airplane, a much larger number of landings would be required so that the probability curves would be extended further into the ranges of lower probability and higher vertical velocities. Such curves would permit the comparisons between the estimated and actual frequency distributions over the complete range necessary for practical applications of the method. However, such an extension of the program did not appear warranted for this initial investigation.

Consistency of Calibration Curves

The foregoing discussion has shown that the calibration obtained during this investigation proved adequate for defining the vertical-velocity probability curve. However, because of the inherent scatter present in the data, it is evident that repetitive calibrations under similar conditions would probably be different. The amount of divergence of the calibration curves to be expected is indicated by the confidence bands appearing in figure 2. These bands imply that, if 100 sets of landings were made under conditions similar to those of the set of 78 landings made in this investigation and the calibration curves were determined for each set, 95 of the curves probably would lie within these bands. Probability curves based on calibrations lying along the extremes as well as diagonals of these confidence bands were derived in order to ascertain the effects of the probable divergence. The results indicated no significant difference at the higher vertical velocities for these extreme cases. However, at the lower vertical velocities some difference did occur, but this range is not considered important for landing-gear design. It was therefore concluded that, despite the scatter attendant on gathering the data, the chances of obtaining a reliable vertical-velocity probability curve are very good (at least 95 chances out of a 100).

A considerable portion of the cost of applying this method depends on the number of landings necessary to calibrate the airplane. The 78 landings gave a reliable calibration curve; however, fewer calibration landings could have been used with only a moderate decrease in accuracy because the standard deviation of the slope of the calibration curve is inversely proportional to the square root of the number of landings comprising the calibration sample (provided all other factors remain unchanged). That is, if as few as one-fourth of the landings had been used, the standard deviation of the slope would be only approximately twice as large.

Calibration Curve for Another Airplane of Same Type

If the calibration curve of one airplane proved valid for all other airplanes of the same type, the large amounts of data required for constructing a probability curve could be gathered in a relatively short time by calibrating one airplane and then measuring the maximum landing acceleration of a number of airplanes of the same type. Data from 49 landings of another airplane of the same type as that used in this investigation were analyzed in order to obtain an indication of how suitable a calibration curve for one airplane might be for another of the same type. These landings had been made to test the trailing-arm velocity indicator rather than to calibrate the airplane and, therefore, the vertical velocities did not cover the wide range considered best for this method. The calibration curve determined from these landings is shown in figure 2 by the dashed line, and for all practical purposes the curve falls within the confidence bands of the calibration curve for the airplane used in this investigation. Since previous study indicated that any calibration curve lying within the 95-percent confidence bands of figure 2 yielded good results, it therefore would appear that the calibration curve obtained from the airplane used to proof-test the trailing arm would give a satisfactory vertical-velocity probability curve for the similar type of airplane used in this investigation.

APPLICABILITY OF METHOD TO A LARGE AIRPLANE

The foregoing discussion has been concerned with a small, relatively rigid, single-engine airplane. In order to test this method for large flexible airplanes an analysis was made of data obtained during 38 landings of a medium bomber airplane. The calibration curve and 95-percent confidence bands, along with the experimental data, are shown in figure 7. For this airplane it also appears that the linear calibration curve would yield acceptable values. The contact vertical velocity at each landing gear was obtained during these landings. The velocity used was the maximum velocity of any gear at contact. Although no large number of conventional landing data was available to check the method, the amount of scatter of the data and the narrowness of the confidence bands appears to indicate that the acceleration method for determining vertical velocities is applicable also to large airplanes.

During 32 of these landings the airplane weight was 95,000 pounds; however, six landings were made at a weight of 120,000 pounds. Although differences in landing weight might be expected to affect the calibration curve, the six heavyweight landings indicated by the square symbols in figure 7 appeared to follow the trend of the lightweight condition. However, owing to the very limited amount of data available for the heavyweight condition, not too much significance can be attached to these data points in this regard.

ANALYTICAL CALIBRATION CURVES

The generalized curves in reference 1 provide an analytical method for obtaining the relationship between the maximum upper-mass acceleration and the contact vertical velocity. This method was applied to the small trainer and bomber airplanes. The necessary values for applying the method to each of the airplanes are given in table II. In addition to these values, figure 11 of reference 1 was also used. The resulting calibration curves are compared with the experimental calibration curves in figure 8. The agreement appears to be very good over the range covered by the experimental data; however, it may be noted that the analytical curves are roughly linear from values of vertical velocity of about 2 feet to 8 feet per second, but become increasingly nonlinear for vertical velocities above 8 feet per second. This result suggests that caution should be used in extrapolating the empirical calibration curves beyond the range of the data.

In order to use the analytical method, assumptions have to be made for the values of tire stiffness characteristics as well as for the orifice diameter at the instant of maximum acceleration. Incomplete knowledge of these landing-gear characteristics at the present time precludes the general use of this method for predicting the calibration. However, future work along these lines may eventually eliminate the necessity for experimental calibration landings.

Another possibility for obtaining the calibration lies in the use of data from the drop tests ordinarily made with the complete airplane.

SUMMARY OF RESULTS

An analysis of data obtained during 268 landings of a small trainer airplane made to investigate a method for obtaining the probability curves for vertical velocity of airplanes at ground contact from maximum incremental center-of-gravity vertical acceleration, together with an analysis of a limited amount of data obtained with a larger airplane, is presented. The results indicate the following:

1. For the small trainer airplane, measurements of maximum incremental center-of-gravity acceleration obtained from 190 routine landings during which the vertical velocity did not exceed 5.2 feet per second yielded cumulative probability curves for vertical velocity which agreed very well with those obtained from the vertical velocities derived from the measurements obtained by a trailing-arm indicator.

2. A calibration curve obtained during limited landing tests of another trainer airplane of the same type showed sufficient agreement to imply that a calibration curve obtained from one airplane may be utilized to provide satisfactory vertical-velocity data for other airplanes of the same type.

3. A limited amount of data obtained during landings of a large flexible airplane indicated the feasibility of obtaining a valid cumulative probability curve of vertical velocity for this type of airplane by the same method used for the small trainer airplane.

4. A possibility exists that the necessity for making calibration landings might be eliminated and replaced by analytical methods or drop tests of the complete airplane.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 21, 1955.

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TABLE I

VALUES OF VERTICAL VELOCITY AND INCREMENTAL CENTER-OF-GRAVITY ACCELERATION

FOR LANDINGS OF A SMALL TRAINER AIRPLANE

(a) Calibration landings

Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps	Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps
1	0.55	2.3	40	0.68	3.6
2	.50	1.1	41	.95	3.8
3	.40	1.6	42	.70	2.1
4	.30	1.6	43	.53	2.0
5	.20	1.0	44	.85	3.6
6	.65	2.8	45	1.05	4.3
7	.80	3.6	46	.75	2.6
8	.50	1.5	47	1.00	2.5
9	1.60	4.4	48	.98	4.3
10	.48	1.3	49	.58	2.0
11	1.12	5.0	50	.83	3.0
12	1.84	6.4	51	.58	1.7
13	.64	3.0	52	1.03	3.4
14	.59	2.9	53	1.26	4.6
15	.64	3.5	54	1.21	4.3
16	1.16	4.5	55	.80	3.2
17	1.03	4.9	56	.70	1.2
18	1.13	4.7	57	1.98	6.9
19	.64	1.7	58	1.52	4.6
20	.61	2.2	59	2.64	7.5
21	.45	1.7	60	.85	3.9
22	.53	2.3	61	2.34	7.7
23	.35	1.1	62	.65	3.7
24	2.26	9.1	63	1.21	5.3
25	1.70	7.0	64	2.00	6.4
26	2.08	8.7	65	.58	2.9
27	.56	2.8	66	.73	4.0
28	1.55	6.8	67	1.65	5.8
29	1.09	4.9	68	2.03	6.0
30	2.31	8.8	69	.61	3.7
31	1.29	5.9	70	1.98	7.1
32	.94	5.0	71	.73	3.7
33	1.32	5.8	72	1.95	7.9
34	.45	1.8	73	.84	4.7
35	.58	3.2	74	1.52	6.8
36	.65	2.2	75	.45	2.0
37	.80	4.0	76	.68	3.7
38	.70	2.0	77	1.09	3.3
39	1.06	3.9	78	.71	3.6

TABLE I.- Continued

VALUES OF VERTICAL VELOCITY AND INCREMENTAL CENTER-OF-GRAVITY ACCELERATION

FOR LANDINGS OF A SMALL TRAINER AIRPLANE

(b) Routine landings

Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps	Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps
79	0.84	3.7	127	0.60	2.8
80	.51	2.0	128	.27	.3
81	.56	2.4	129	.35	.9
82	1.24	3.3	130	.58	2.5
83	.43	2.0	131	.43	.6
84	1.06	4.0	132	.60	1.1
85	.58	2.4	133	.93	3.5
86	.73	2.5	134	.50	2.0
87	.53	1.1	135	.35	1.0
88	.48	1.7	136	.17	1.4
89	.58	2.8	137	.43	1.0
90	.91	2.7	138	.65	2.3
91	.33	.5	139	.40	2.0
92	.10	.8	140	.38	1.6
93	.22	.5	141	.45	.8
94	.22	1.1	142	.81	3.3
95	.75	2.3	143	.28	.5
96	.25	.3	144	.38	1.4
97	.25	1.0	145	.45	1.0
98	.15	.9	146	.78	2.8
99	.17	.6	147	.35	2.1
100	.22	.5	148	.35	1.4
101	.30	1.5	149	.45	1.7
102	.22	.8	150	.35	1.1
103	.70	2.6	151	.38	1.4
104	.15	1.1	152	.30	1.5
105	.75	2.2	153	.63	3.3
106	.58	1.8	154	.27	1.3
107	.43	.9	155	.55	2.1
108	.83	2.4	156	.45	1.2
109	.33	.9	157	.43	1.0
110	.17	.6	158	.25	.6
111	.35	1.7	159	.33	1.0
112	.53	1.9	160	.43	1.4
113	.10	.4	161	.22	1.3
114	.71	1.3	162	.25	1.3
115	.56	2.3	163	.63	2.1
116	1.20	2.7	164	.55	1.7
117	.74	3.3	165	.63	2.6
118	.64	1.4	166	.68	3.0
119	.69	2.5	167	.45	1.6
120	.97	2.4	168	.07	.7
121	.69	2.7	169	.43	1.6
122	.43	2.2	170	.40	1.6
123	.38	1.8	171	.40	2.0
124	.56	2.8	172	.38	1.3
125	.59	3.7	173	.55	1.8
126	.23	.9	174	.48	1.6

TABLE I.- Concluded

VALUES OF VERTICAL VELOCITY AND INCREMENTAL CENTER-OF-GRAVITY ACCELERATION

FOR LANDINGS OF A SMALL TRAINER AIRPLANE

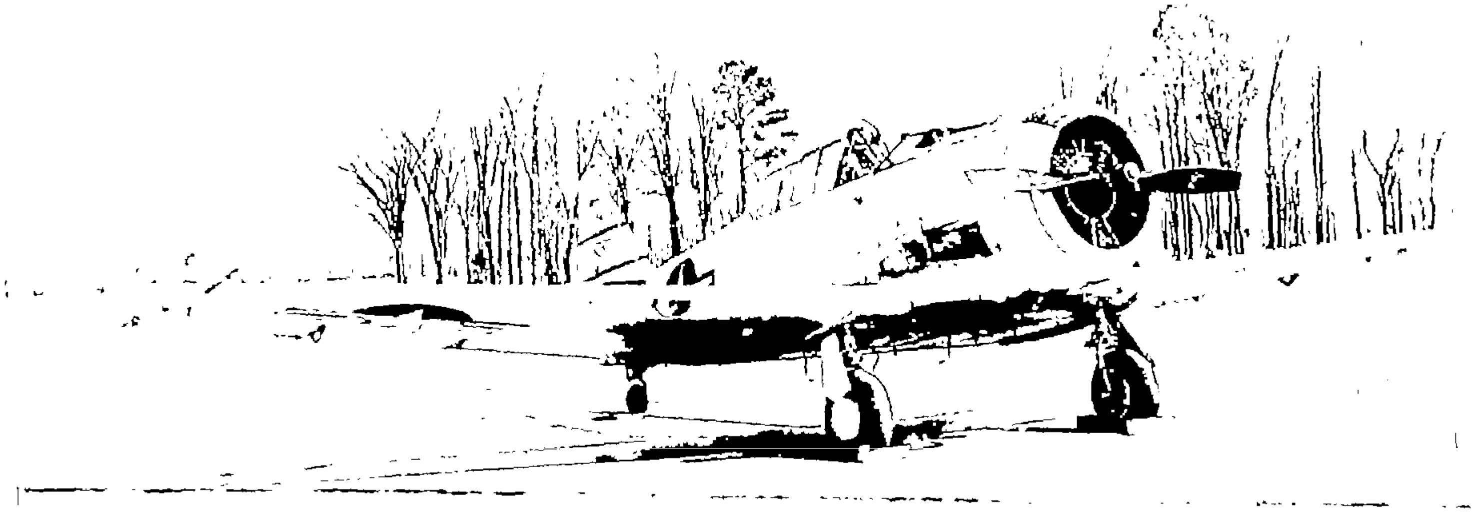
(b) Routine landings - Concluded

Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps	Landing number	Maximum incremental c.g. acceleration, g units	Vertical velocity, fps
175	0.45	1.4	222	0.23	0.8
176	.48	1.5	223	.56	1.2
177	1.05	4.1	224	.45	.8
178	.48	2.1	225	.30	1.4
179	.45	1.5	226	.33	1.4
180	.60	2.4	227	.35	.9
181	.55	3.2	228	.53	1.9
182	.58	1.6	229	.43	2.6
183	1.00	3.5	230	.63	2.1
184	.73	1.6	231	.10	.4
185	1.36	2.5	232	.30	1.5
186	.65	2.5	233	.28	.7
187	.68	2.8	234	.28	1.5
188	.65	2.3	235	.54	2.3
189	.40	1.9	236	.33	.8
190	.73	2.7	237	.69	3.4
191	.40	1.3	238	.41	1.7
192	1.28	5.2	239	.43	1.6
193	.84	4.2	240	.28	1.2
194	.33	1.1	241	.48	2.4
195	.61	2.5	242	.46	1.3
196	.38	.9	243	.56	1.5
197	.35	.9	244	.46	2.2
198	.30	.7	245	.46	1.5
199	.20	.6	246	.33	1.3
200	1.05	4.0	247	.23	.9
201	.75	2.3	248	.25	1.1
202	.40	1.1	249	.41	1.6
203	.72	1.7	250	.28	1.1
204	.17	.8	251	.41	1.1
205	.35	.5	252	.43	.9
206	.35	1.1	253	.35	1.2
207	.62	2.2	254	.25	1.2
208	.47	1.2	255	.55	2.0
209	.62	2.0	256	.65	2.4
210	.47	1.1	257	.55	2.8
211	.80	1.8	258	.58	2.5
212	.64	2.0	259	.73	2.9
213	.59	2.0	260	.80	3.3
214	.23	1.3	261	.43	1.6
215	.46	1.8	262	.65	3.0
216	.41	1.4	263	.55	3.3
217	.28	.9	264	.78	3.3
218	.28	.5	265	.53	2.6
219	.28	1.3	266	.38	2.0
220	.33	1.0	267	1.03	4.6
221	.56	1.6	268	.33	.7

TABLE II

VALUES USED IN APPLYING ANALYTICAL METHOD

	Trainer airplane	Bomber airplane
Hydraulic area of shock strut, sq ft	0.04708	0.41968
Orifice coefficient	0.9	0.9
Mass density of hydraulic fluid, slugs/cu ft	1.652	1.652
Net orifice area (at instant of maximum acceleration), sq ft	0.000493	0.003598
Weight (on one landing gear), lb	2,500	47,500
Tire-deflection constant, lb/ft	18,500	68,000



L-88242

Figure 1.- Trainer airplane used in this investigation.

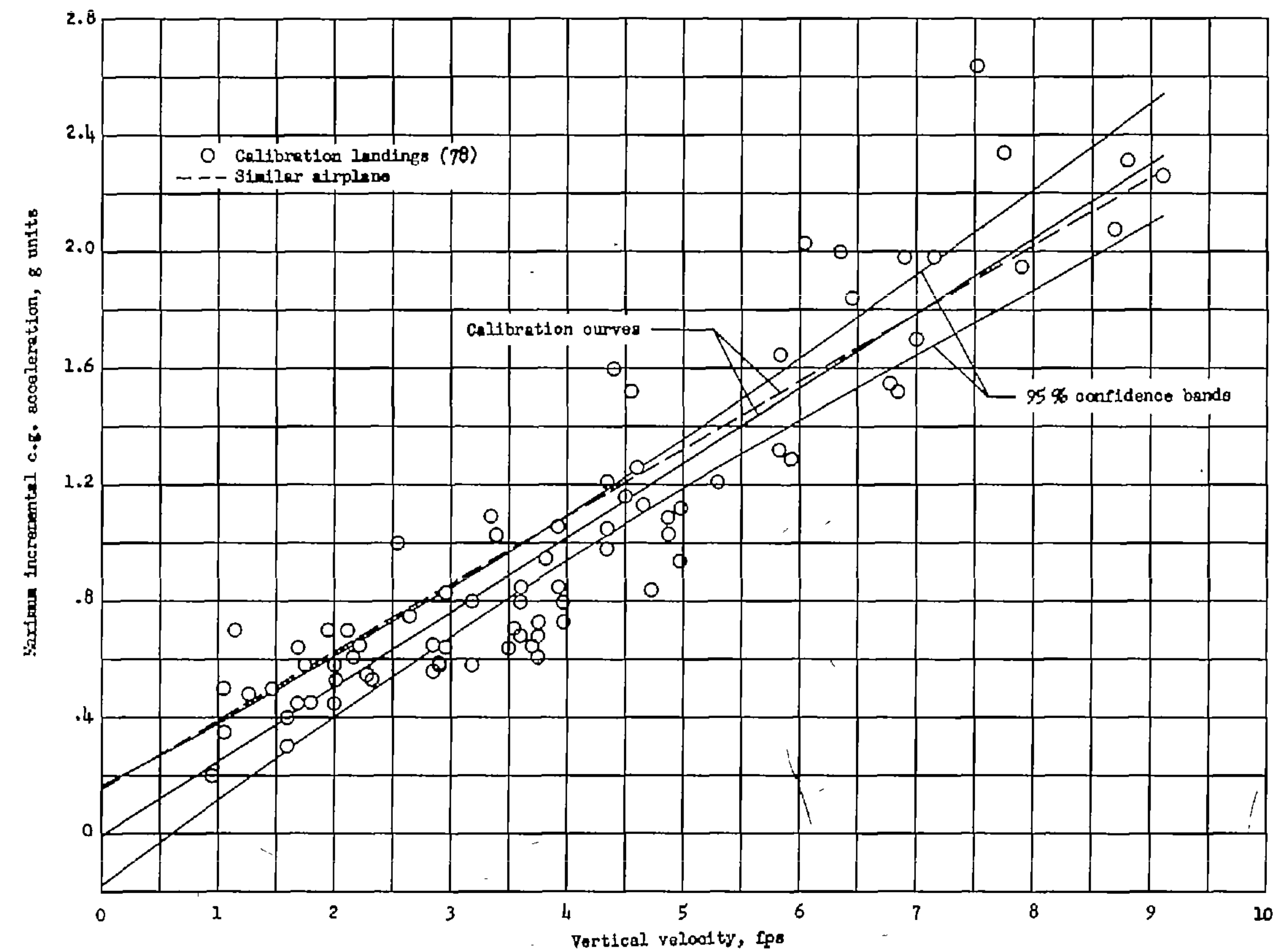


Figure 2.- Calibration curves and confidence bands for small trainer airplanes.

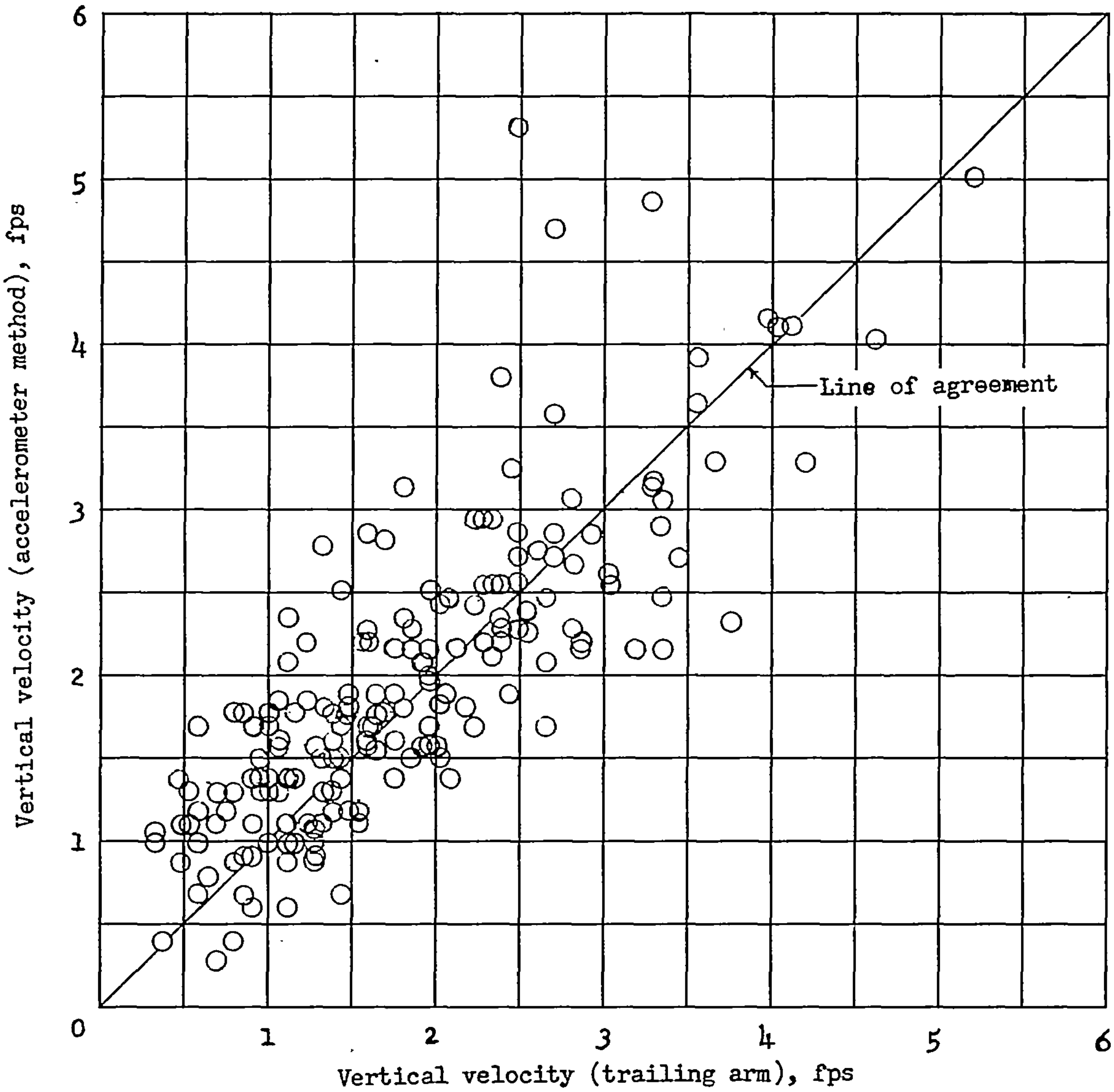


Figure 3.- Comparison of velocities obtained from accelerometer with those obtained from trailing-arm velocity indicator.

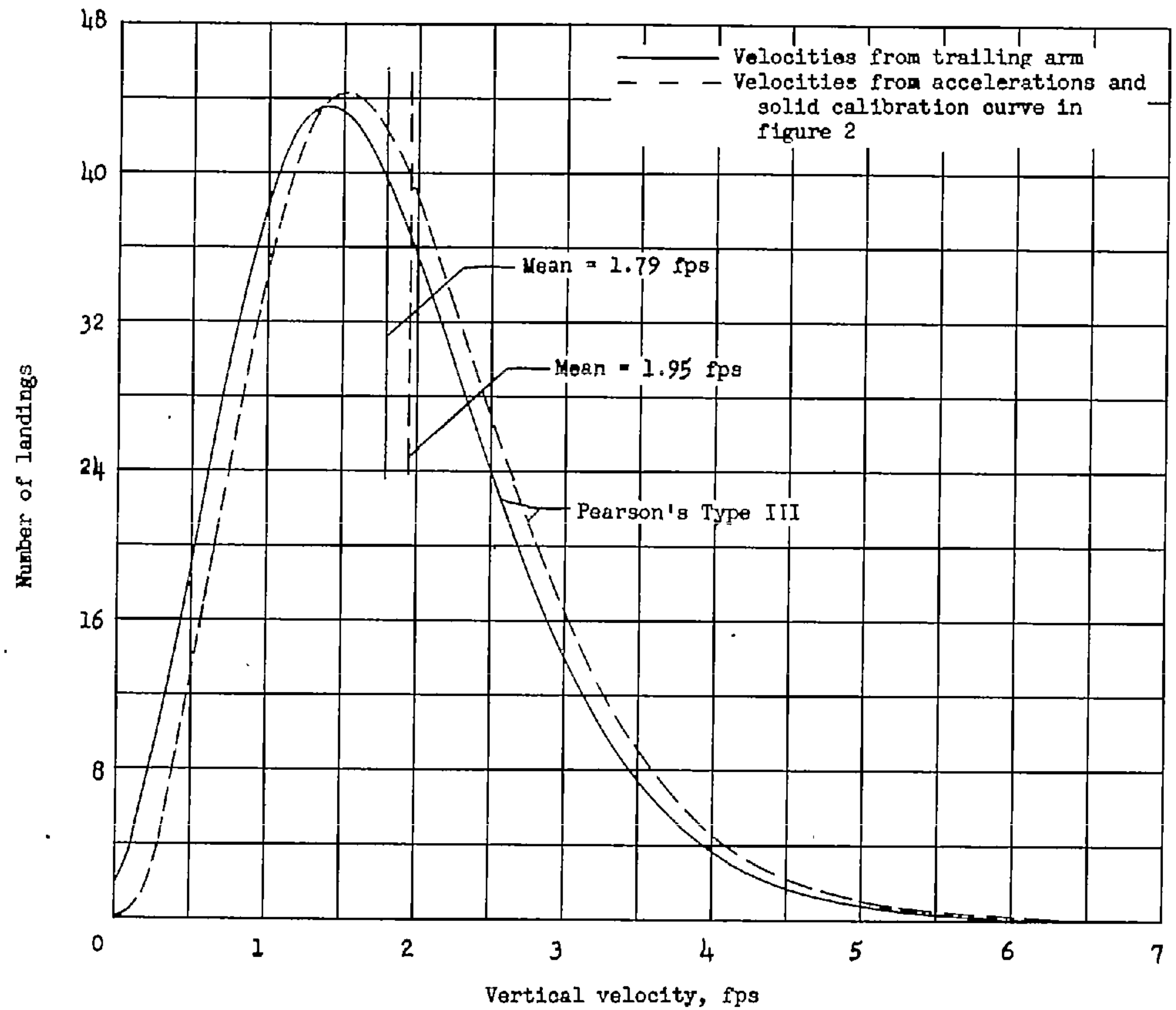


Figure 4.- Frequency distributions for vertical velocities for 190 routine landings of a small trainer airplane.

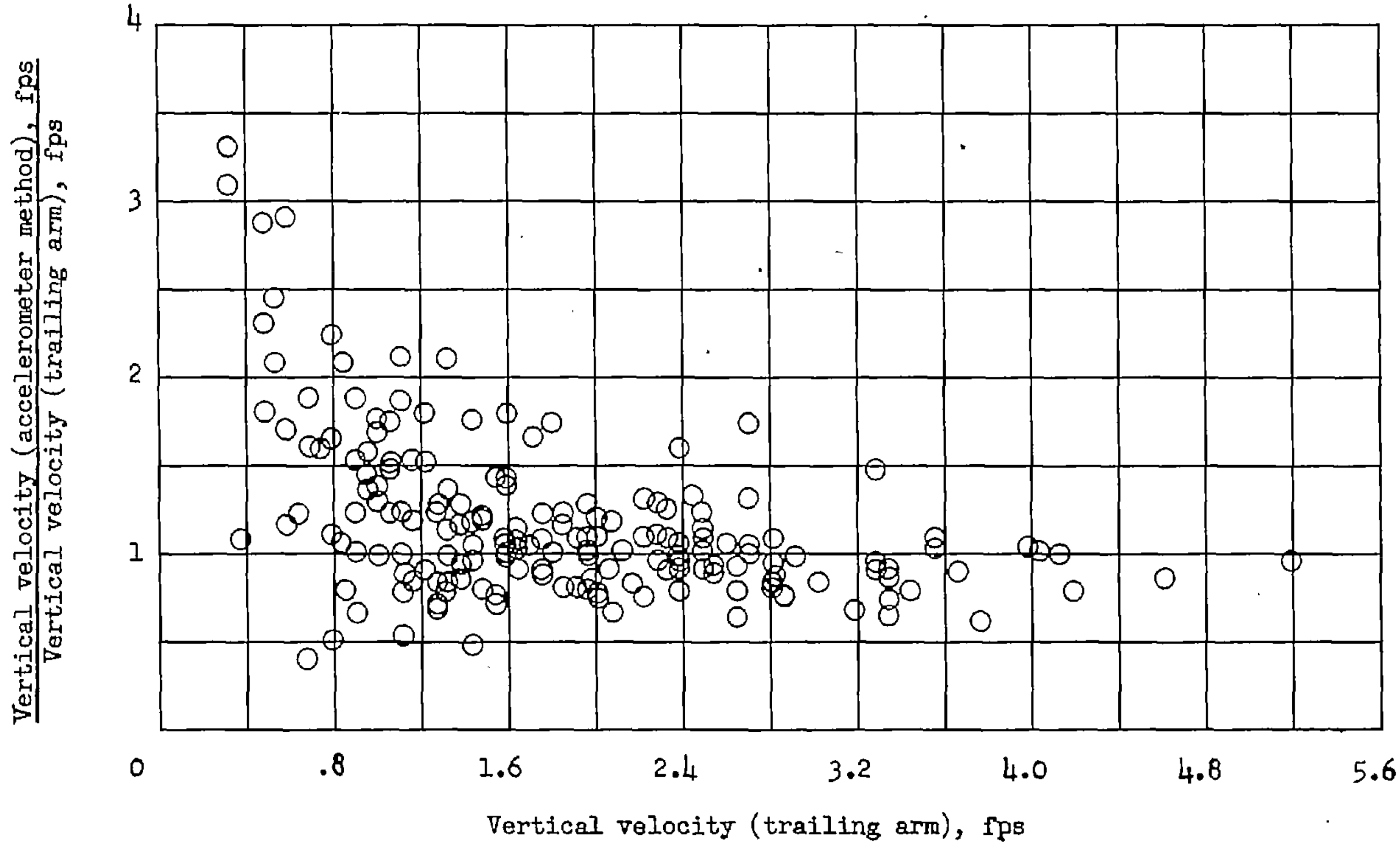


Figure 5.- Variation of ratio of vertical velocity obtained by acceleration method to vertical velocity obtained by trailing-arm indicator with velocity obtained by trailing-arm indicator.

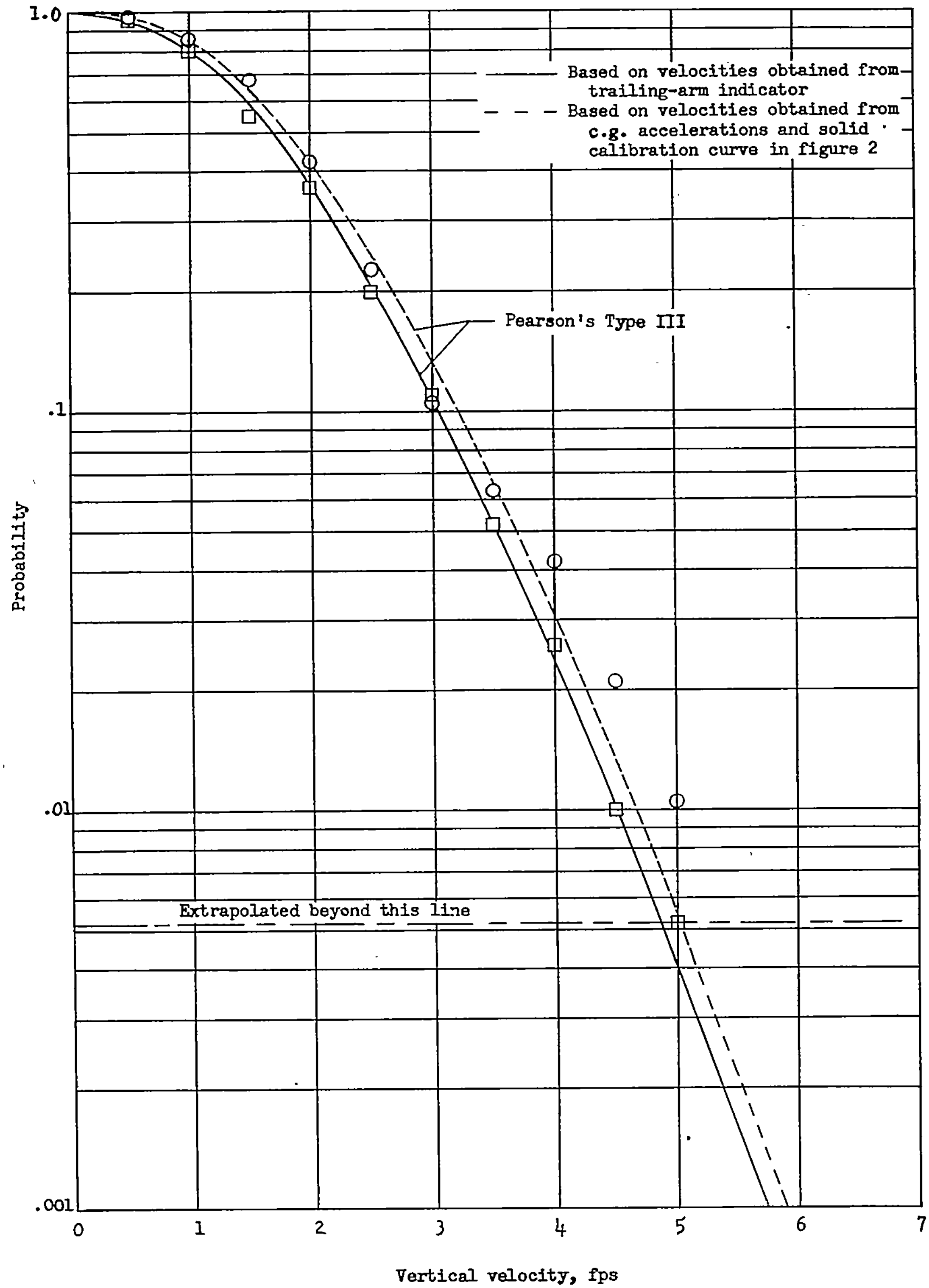


Figure 6.- Probability of equaling or exceeding a given vertical velocity.